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Advances in the assessment of drystone retaining walls – some case studies

Les progrès dans l'évaluation des murs de soutènement en pierres sèches : études de cas

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ABSTRACT Drystone retaining walls have played an essential part in the infrastructure of hilly and mountainous regions around the world, and have provided platforms for building and for agricultural terraces. Research carried out in England and in France has led to a good understanding of their behaviour, but it is difficult to determine the details of the construction of individual walls without dismantling them, and so it can be hard to tell whether or not apparent defects and deformations are a threat to stability. Replacing every apparently defective or deformed wall would be a waste of resources, yet dismantling a wall would obviously be completely disruptive to its function. Invasive investigation, such as drilling, could easily cause damage to the wall structure and destabilise the wall. There is therefore a pressing need for non-disruptive methods of investigation that can reveal critical aspects of a wall's construction. Thermal imaging carried out in the right conditions can reveal important information about aspects of a wall's construction that are critical to its stability. This paper presents case studies that have contributed to the development of this technique, and demonstrate its potential.

RÉSUMÉ Les murs de soutènement en pierres sèches ont joué un rôle essentiel dans l'infrastructure des régions vallonnées et montagneuses à travers le monde, et ont fourni des plates-formes pour la construction et pour les terrasses agricoles. Les recherches menées en Angleterre et en France ont conduit à une bonne compréhension de leur comportement, mais il est difficile de déterminer les détails de la construction de chaque mur sans le démonter, et il peut donc être difficile de dire si les pathologies et déformations apparentes sont graves. Le remplacement de tous les murs suspects serait un gaspillage de ressources et le démantèlement d'un mur détruirait évidemment complètement sa fonction. Des sondages comme les forages, causent des dommages à la structure de la paroi et déstabilisent le mur. Il existe donc un besoin urgent de méthodes d'évaluation non- destructives qui peuvent révéler des aspects essentiels de la construction d'un mur. L'imagerie thermique effectuée dans de bonnes conditions peut révéler des informations importantes sur le mode de construction d'un mur qui sont essentielles à sa stabilité. Ce document présente des études de cas qui ont contribué au développement de cette technique, et qui démontrent son potentiel.

1 INTRODUCTION

Drystone construction has been used for retaining walls since ancient times. Stones usually come from close to the construction site, and are of a size that can be moved by hand - though some cultures, most notably in South America, have used very large stones.

Because drystone walls use local materials and no form of mortar, they are a very low-energy and sustainable form of construction, and blend well in their landscapes. Indeed, in many hilly and mountainous areas, the drystone walls are an important part of the landscape.

Drystone walls rely for their stability on the quality of the stone used, and the skill and knowledge of the builder.

The quality of stone determines first of all its ability to transmit the forces required. The height of any construction is likely to be insignificant in comparison with the depth of material which has consolidated the stone when it was in its original geological setting, but within the wall loads are transmitted through small points of contact which may result in localised high stresses. The stones may also be subject to some bending stresses if they are not adequately supported.

The main concern with the stones is the durability of the material. Within a wall, the way in which the exposed stone deteriorates over time may not match what is happening to the stone hidden behind the wall face. Wind and rain, as well as providing mechanical weathering of a kind which will not be experienced by the hidden stone, will tend to remove any weakened material, and it may not be obvious that this is happening. Wetting and drying, and biological weathering can lead to the progressive deterioration of the strength of some stone that might be used for drystone retaining walls.

Figure 1. Front and back faces of an experimental wall constructed in France, reflecting normal good practice for construction in granite.

The quality of the stone is however relatively easy to ascertain from visual inspection. The quality of the construction can be concealed. A carefully made stack of blocks will resist earth pressures, but the great strength of drystone walls is their ability to tolerate uneven and variable loading and support, by redistributing load within their construction via good overlaps between carefully laid stones (McCombie et al. 2012). Because of the retaining function, the vertical load near the front of the wall is greater than that at the back, and this combined with the fact that the front face is what is seen by the client leads to the construction of the face often differing significantly from that at the back, as can be seen in the test wall shown in Figure 1. The wall shown was extremely strong and stable, despite the difference in appearance between the two faces. The builders of this wall rank among the best in the world, and the quality of the construction was very high.

Further test walls on the same site showed that when the builders were asked to construct with less regard to the appearance of the face (*paysan* style), the overall density of the construction was identical to that of an equivalent 'engineer style' wall which had excellent visual appearance but took twice as long to build. In this case, the construction style adopted for an engineering client was no more sound than what would be built for any client - it just looked tidier, and cost more.

Assessment of existing drystone retaining walls is therefore far from simple, because the construction that cannot be seen is critical. The fill placed behind the wall, and the width of the wall near its crest could be ascertained with a small excavation, if that were possible, but to obtain all the information an engineer would ideally like to have would require dismantling of the wall, which would defeat the object of making an assessment.

2 INVESTIGATION REQUIREMENTS

Key features to identify in dry stone wall assessment include:

- wall porosity - the gaps between the stones must be clear for the wall to maintain its free-draining nature, and so preclude the development of positive pore water pressures;
- wall and stone dimensions;
- condition of the stone;
- good bonding and appropriate use of through-stones.

The wall porosity can be investigated comparatively easily, assuming safe access to the wall face is possible, because gaps between stones are usually sufficient to allow visual inspection and probing with wires. The use of an endoscope might also assist, but the authors have not investigated this. Sometimes a careful visual inspection has revealed that the builders used mortar, whilst trying to present the outward appearance of drystone. Where this has been found, the mortar has been used only in patches, and has not obstructed the permeability of the walls.

Determining the dimensions of a wall can be difficult, as normally neither the founding level nor the back of the structure can be accessed without risking damage to the structure itself, and perhaps to the inspector. If the visual inspection described above is possible, it can allow measurements of the minimum thickness of the wall, but this can be confusing if rubble from the construction has been used as backfill immediately behind the wall.

The condition of the stone might also be assessed during the visual inspection, but some stones deteriorate through their thickness rather than at the surface, so this can be hard to tell.

The final requirement will be the concern of the remainder of this paper. A common form of wall construction in the United Kingdom, where drystone is used predominantly for field walls, is to have a clear front and back face to the wall with rubble filling the space in between. For a wall to resist earth pressures, it is crucial that the front and back faces are tied together, so that the wall cannot be overturned without the wall behaving essentially as a monolith (Figure 2). If the front and back faces can act independently, with the rubble between just rearranging itself a little, then the resistance is very much reduced. In this form of construction, through-stones are used, spanning the full thickness of the structure to tie the two faces together. It is also important that the rubble fill is made of tightly packed large pieces of strong stone which can be locked together by the through-stones. Therefore if this fill has been constructed properly, it will be almost impossible to see through to the back face of the wall.

In the mountainous regions of southern France, drystone has been used principally to form earth-retaining structures and revetments, through-stones do not have the same importance, because good construction practice ensures that there is good bonding, that is, overlap with stones above and below and to either side, throughout the thickness of the construction. This means that each stone rests on two or more stones beneath, so making it difficult for them to be moved apart. This in effect produces a directional tensile strength within the structure (McCombie et al. 2012) which extends from front to back, as well as along the length of the wall. In the two-faced construction style, tensile connection between front and back of the wall only exists where there are through-stones.

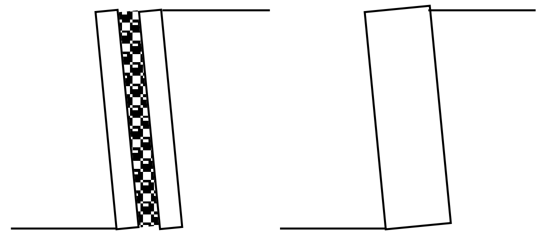

Figure 2. The importance of a wall behaving monolithically.

The most fundamental thing to assess about a drystone wall's construction is therefore how well connected the front face is to the back face. The presence of any large voids or loose material between the two will mean that the back face is resisting the earth pressure on its own. This effect has been seen in some partial failures, where patches of the front face fall away, leaving the rest of the wall standing (but often not for very long).

3 THERMAL INVESTIGATIONS

The frequency and firmness of connections between the back of the wall and the face help to determine its capacity to conduct heat. The earth retained by the wall changes temperature much more slowly than the surface of the soil or the stone at the face of the wall, and will probably not show a detectable change over a 24 hour period. On the other hand, the stone at the wall face is exposed to the weather - wind, rain, and heat from the sun, all of which will depend upon the wall's orientation. Even with none of these weather effects, the stone at the face will lose heat to the air, or gain heat from the air, through conduction.

The temperature of the stone at the face of the wall reflects these surface processes, but is also affected by the flow of heat within and between the stones which is driven by temperature gradients. Hence stones that have better thermal contact with the rear of the wall, such as through stones, would be expected to show a difference in temperature to those surrounding them. These temperature differences may not be obvious to the touch, but by using a thermal imaging camera which has a high sensitivity they can be detected, so revealing aspects of the hidden construction of the wall. In this way other features such as water build up or voiding behind the wall may also been seen. Thermal imaging has one particular advantage over other methods of investigation - it can be done at a distance, without requiring any physical contact with the wall. This can be important if the stability of the wall is in question, or if there is a road immediately in front of it, for example.

3.1 *First trial*

In order to explore this approach thermal imaging has been carried out on a number of walls in the UK and in France. This work was carried out at varying times of the day and on a number of walling types in order to assess the range of construction types for which the technique might work, and if there are optimum conditions for its use.

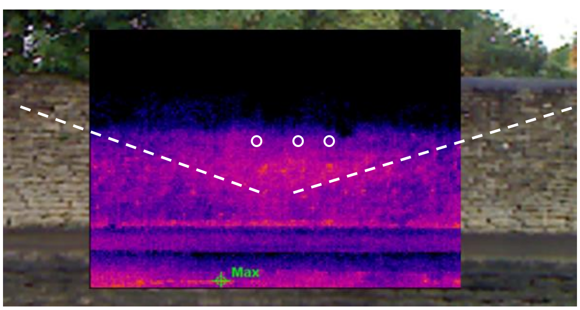

Figure 3. Thermal image of a limestone wall in Wiltshire, UK, overlaid on the visible light image.

The first trial image is shown in Figure 3, superimposed on the visible light image. This image was taken early one morning, following a cold night. A number of features can be seen. The wall retains about 1m of fill, and is at the back of a footpath which is itself supported on a small wall of five courses alongside the road. The wall carries a parapet, which shows dark on the thermal image because it is the same temperature as the air. On the other hand, the retaining wall beneath it shows lighter because it is warmer, even after the cold night. Part of this wall has been repaired following a failure (demarcated by dashed lines); the repaired area shows warmer than the adjacent wall, presumably because the fill within the wall has been packed carefully and so has conducted heat from the backfill more effectively. The darker areas below the repair probably indicate parts of the wall which were loose but were not involved in the failure. At the right hand edge of the thermal image is another brighter area which was presumably built well enough to begin with so that it has remained sound. Within the repaired area are a small number of regularly spaced hot spots, which almost certainly correspond to through-stones (three are marked by circles). Some of these interpretations can be confirmed to an extent by listening to the sound on hitting the wall with a hammer, but this is to be done only with appropriate caution, and is not an approach which this paper addresses.

3.2 *24 hour study*

A 24 hour study was subsequently carried out of a limestone wall near Northleach in the Cotswolds, UK. Images were taken at regular intervals, to determine the validity of this technique as well as to gain an idea of the optimum time to take images.

The wall is over 200m long and has many sections of varying construction, some in poor condition. One length was rebuilt in 2011, with unusually large through-stones and soil-reinforcement in the backfill connected to the wall using galvanised steel bars. Two of the authors visited the wall during the construction process, and it is well documented, making it a good test for this method. The wall is south facing and exposed to the sun throughout the day. Four other sections of the wall were also imaged in conjunction with this section.

In addition to simply obtaining the thermal images, some specific points were identified regarding the use of thermal imaging for this type of investigation. These are explained below, and illustrated using Figures 4-6. Within the new wall section the through-stones were easy to see using the thermal imaging camera, as shown in Figure 4. This image was taken late at night when the air had cooled down after a warm day. The through-stones in this section were visible using the thermal imaging throughout the 24 hours, but became less prominent when direct sunlight first came onto the wall in the morning (8am readings); the through-stones appeared cooler than the rest of the wall in most of the images taken.

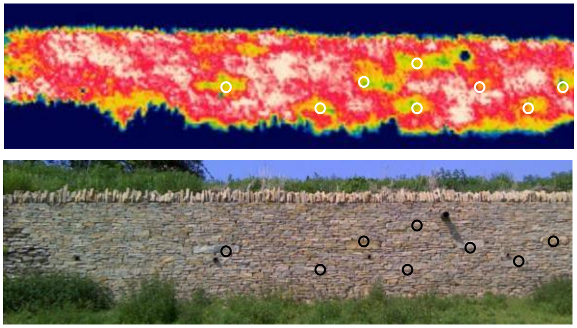

Figure 4: Thermal image of new wall section at Northleach, UK. Some of the most conspicuous through-stones have been marked with circles.

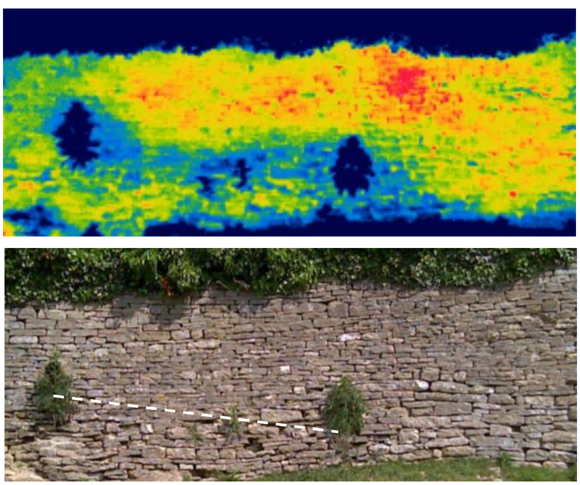

Figure 5: Thermal image of older wall section showing potential area of water (along the dashed line)

Other potential features appeared in the thermal images of the older sections of wall; for example, an area of wall which may be affected by water appears cooler in Figure 5. This area was not obvious at the face of the wall but the presence of vegetation is indicative of the presence of moisture. This feature was only visible in the late evening and early morning when the wall was cooler.

The influence of shading can be a problem for thermal imaging, as shown in Figure 6. Part of the wall is shaded by a large tree, and where this shading occurred very little thermal information could be gathered in comparison to the unshaded adjacent areas. This effect was still present once direct sunlight was no longer present on the wall.

Figure 6: Thermal image showing the effect of shading.

3.3 *French Study*

Following the work at Northleach a 3 day field study was carried out in the Cévennes area of France. This study presented the opportunity to use thermal imaging on walls constructed using larger stones than typically found within the UK, as well on a variety of different construction styles. This investigation was aided considerably by the guidance of those who had built some of the walls being investigated, as they could give great detail on the construction principles, and provide comments on the thermal images.

This work provided more insight into how thermal imaging may be used to provide greater understanding of what is happening behind the wall face. In the English walls, the through-stones were sometimes obvious due to their larger size. In the French construction more emphasis is placed on good bonding throughout the wall, including from front to back, and through-stones are not always used. It became clear that one cannot assume that large stones are through-stones. In the granite wall shown in Figure 7, for example, there are a number of stones that at the wall face appear to be very similar, and so might be expected to show a similar temperature. However this is not the case, implying that they extend to different depths within the wall face itself, or that some of these stones taper whereas others are blockier in shape, so making different contributions to the stability of the wall.

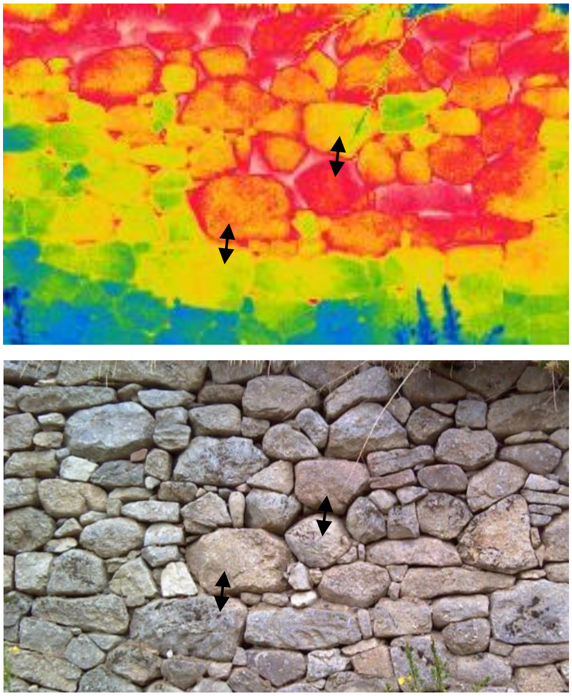

Figure 7: Thermal image showing significant temperature differences between stones that initially appear to be of similar size (indicated by arrows).

The converse of this was also seen, with the thermal imaging indicating stones which appeared small at the wall face must extend much deeper into the wall than expected.

4 DISCUSSION

The cases presented have shown that thermal imaging can identify important characteristics of a drystone retaining wall. The clearest is the distribution of through-stones, which are critical to the stability of the two-faced form of construction most common in the UK. In France, where there is a greater emphasis on good bonding than on through-stones, the thermal images indicate how far stones might penetrate into the wall, revealing the effectiveness of the bonding. The images can also indicate the overall density of the construction, as this affects the transmission of heat from the backfill to the face of the wall, and can thus reveal areas of a wall which may not have been constructed sufficiently well.

The timing of the thermal imagery is very important. Early in the morning following a cold night seemed to show the clearest information. Analytical work is being carried out by the authors to explore this aspect further.

Thermal imaging can also indicate the presence of water within a wall, a critical issue for wall stability.

5 CONCLUSIONS

Thermal imaging can be used to identify wall features that are not visible using conventional, non-destructive wall assessment techniques. The thermal response of individual wall stones to atmospheric temperature variations indicates the thermal mass and connectivity of the wall stones. This can be used to help identify features such as the depth of retained fill, historic wall repairs, areas of high moisture and the presence of through-stones.

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